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Vertical temperature and density patterns in the Arctic mesosphere analyzed as gravity waves

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ABSTRACT

Three series of rocket soundings were conducted from high latitude sites during winter. In the first series, four pitot pressure soundings were launched during a 13-hour period from Ft. Churchill, Canada (59° N) on January 31, and February 1, 1967. The second series consisted of one pitot sounding and two grenade soundings carried out during a 3-hour period on January 13–14, 1970. Temperature and wind profiles and one density profile were observed independently to obtain the thermodynamic structure, the wind structure, and thus their interdependence in the mesosphere. The third series of soundings was conducted from Point Barrow, Alaska (71° N) on December 6, 1971. This series consisted of five soundings of which the first two and the last two were pitot–grenade pairs. Temperature profiles from all soundings in each series were averaged, and a smooth curve (or series of smooth curves) drawn through the points. A hydrostatic atmosphere based on the average, measured temperature profile was computed, and deviations from the mean atmosphere were analyzed in terms of gravity wave theory. The vertical wavelengths of the deviations were 10–20 km, and the wave amplitudes slowly increased with height. The experimental data were matched by calculated gravity waves having a period ranging between 15 and 80 minutes and horizontal wavelengths of 60 to 280 km. Our interpretation is generally consistent with the results of others who have studied gravity-acoustic waves in the atmosphere. The wind measurements are consistent with the thermodynamic measurements. The results also suggest that gravity waves travelled from East to West with a horizontal phase velocity of approximately 60 m/s.

1. Introduction

The present paper treats several series of rocket soundings of atmospheric temperature, density, and wind structure. The soundings are of two types, pitot and grenade. For the former, a pitot stagnation probe is mounted on a rocket vehicle, whose position and velocity are measured by radar tracking. For an incompressible fluid, we have the simple formula

$$\rho = \frac{2(P^0 - P)}{u^2} \tag{1}$$

Density is determined if stagnation pressure, static pressure, and velocity are measured. Addition of compressibility makes the analysis somewhat more involved without affecting the basic principle presented above (Horvath et al., 1962). For the grenade experiment, a series of grenades are exploded in the atmosphere, and the position and time of each explosion is determined. The time, and direction of arrival of the spherical sound pulse are measured by a ground based microphone array. This information is used to deduce the mean temperature and horizontal wind speed in atmospheric slabs whose thickness varies between 2 km and 4 km depending on the particular grenade payload used (Nordberg and Smith, 1964).

Essentially, the pitot technique provides a high vertical resolution (0.5 km) direct measurement of atmospheric density, while the grenade technique gives a direct measure of atmospheric temperature and horizontal wind with a 2–4-km vertical resolution. For both techniques, the time to make the atmospheric traverse is approximately 1 minute, resulting in a virtually instantaneous picture of the vertical structure.

2. Outline of gravity wave theory

Waves in a stratified fluid under the influence of gravity appear to have been initially discussed by Burnside (1889) and Love (1891). Both authors treated an incompressible fluid. Görtler (1943) used schlieren photography to show experimentally that disturbances in an incompressible stratified medium under the influence of gravity propagate along characteristic rays. Lamb (1909) treated a compressible, adiabatic, ideal gas whose density is stratified by gravity. Since the early contributions by Burnside, Love, and Lamb, there have been many theoretical papers on various types of gravity waves. Reasonably up-to-date treatments of the subject may be found in Eckart (1960), Yih (1965), and Tolstoy (1973).

The simple theory involves linearizing the atmospheric equations of motion and specifying a sinusoidal solution, i.e.,

$$\phi = \phi_0 \exp\left[-i(\omega t + k_x x + k_z z)\right] \tag{2}$$

Perturbations in pressure, density, temperature, and gravity wave generated wind are related to ϕ by what Hines (1960) has called polarization relations, and a dispersion relation which has the form:

$$n_z^2 = \left\{1 - \left(\frac{\omega_A}{\omega_B}\right)^2\right\} - n_x^2 \left\{1 - \left(\frac{\omega_B}{\omega}\right)^2\right\} \tag{3}$$

where

$$n_x = \frac{k_x a}{\omega} \quad n_z = \frac{k_z a}{\omega} \tag{4}$$

(Pitteway and Hines, 1963).

Since atmospheric gradients are usually weak, the ray approximation for vertical wave propagation was used. Volland (1969a) has shown that the ray treatment is a sufficient approximation for gravity waves propagating obliquely upwards, provided the horizontal wave number is in the order of, or greater than ω/a, where a is the sound speed, and ω is the circular frequency of the wave. This statement is equivalent to the requirement that the horizontal phase velocity must be less than the sound speed. For vertical wavelengths up to 20 km, the ratio of phase velocity to sound speed tends to be less than 0.25.

The next problem which comes to mind is how to take account of background wind. The frequency of a moving fluid particle, or the "intrinsic frequency" may be defined as

$$\Omega = \omega - \mathbf{k} \cdot \mathbf{U} \tag{5}$$

where **U** is wind velocity.

The conditions under which the above procedure is valid have been discussed by Jones (1969), and are essentially satisfied. Experimentally, it turns out to be very difficult to obtain a good value of the background wind **U**. On one hand, a large number of wind soundings is needed to average out the gravity wave contribution. On the other hand, the velocity **U** is relative to the layer in which the gravity waves are generated, a fact which adds further complication to Equation (5). Finally, the vector nature of the equation requires some prior knowledge of the direction in which the gravity wave is propagating. However, a phenomenon which was originally viewed as an imperfection in the measurement technique, has turned out to be useful in this respect. The rocket trajectory is at an angle to the vertical, resulting in a horizontal vehicle velocity of some 250 m/s, and a horizontal travel distance of 12 km during the measurement. Examination of the experimental curves shows that the wavelength decreases with altitude. Thus the rocket is going into the wave train. Since the launch direction from Pt. Barrow is due east, we may conclude that the wave train is coming from an easterly direction. The same situation prevails at Ft. Churchill. Our results suggest that the waves in these instances travelled from East to West. Thus it becomes possible to use an estimated wind **U**, relative to the layer at which the rocket measurement begins, i.e., approximately 35 km.

3. Experimental procedure

The experimental data consist of three winter series of rocket soundings from high latitude sites. In the first series, four pitot soundings were conducted during a 13-hour period from Ft. Churchill, Canada (59° N) spanning January 31 and February 1, 1967 (see Table 1) (Smith et al., 1969). The second series consisted of three soundings carried out during a 3-hour period on January 13–14, 1970 from Churchill (Smith et al., 1972). The first sounding was made with the acoustic

Table 1. *Launch sequence of first series. Fort Churchill (59° N); 1967*

GMT	Date	Time after first shot	Type
2317	Jan 31	0h00m	Pitot
0538	Feb 1	6h21m	Pitot
0826	Feb 1	9h09m	Pitot
1158	Feb 1	12h41m	Pitot

Table 2. *Launch sequence of second series. Fort Churchill (59° N); 1970*

GMT	Date	Time after first shot	Type
2223	Jan 13	0h00m	Grenade
2351	Jan 13	1h28m	Pitot
0135	Jan 14	3h12m	Grenade

Table 3. *Launch sequence of third series. Point Barrow (71° N); 1971*

GMT	Date	Time after first shot	Type
0300	Dec 6	0h00m	Pitot
0302	Dec 6	0h02m	Grenade
0442	Dec 6	1h42m	Pitot
0752	Dec 6	4h52m	Pitot
0802	Dec 6	5h02m	Grenade

grenade technique to measure the temperature and wind profiles in the 35–90 km region; the second sounding was a pitot probe launched 88 minutes later to measure the density profile; and the last sounding employed the acoustic grenade technique 104 minutes after the pitot sounding (see Table 2). The third series of soundings was conducted from Point Barrow, Alaska (71° N) on December 6, 1971 (Smith et al., 1974). This series consisted of five soundings, of which the first two and last two were pitot–grenade pairs. The remaining sounding was performed with a pitot probe. The objective of launching such pairs was to obtain high vertical resolution thermodynamic structure (pitot) and wind information (grenade) simultaneously. The series commenced at 0300 GMT with a pitot probe, which was followed by a grenade at 0302 GMT. These profiles were flown over essentially the same trajectory only 2 minutes apart. The remaining soundings, a pitot at 0442 GMT, a pitot at 0752 Gmt, and a grenade at 0802 GMT completed the series (see Table 3). In the second and third series of soundings, the temperature and wind profiles from the grenade technique and the density profiles from the pitot technique provided independent examination of the thermodynamic structure, the wind structure and the relationship of each in the mesosphere.

4. Analysis of data

Temperature profiles from all soundings in each series were averaged and a smooth curve drawn through the points. A hydrostatically determined atmosphere based on the average measured temperature profile was computed. Deviations from this mean hydrostatic atmosphere were then considered.

The hydrostatic equation and the equation of state are used to obtain the remaining two thermodynamic parameters in both the grenade and pitot techniques. Such an approach assumes that vertical accelerations in the atmospheric motions are negligible relative to the acceleration due to gravity, and is valid for mean atmosphere calculations. Smith et al. (1968) compared the results of grenade soundings and pitot probe soundings at Wallops Island, Va. They found temperature agreement to be better than 3 K below 60 km and better than 5 K between 60 and 90 km altitude, confirming the validity of the hydrostatic approximation for background atmosphere calculations.

For the first test series, the ratio of the density measured by the pitot probe to the hydrostatically computed density (based on the average temperature profile) was plotted as a function of altitude for each probe. The density variations are shown in Fig. 1. Fig. 2 shows the corresponding power spectral density versus wavelength for atmospheric density variations between 28 km and 80 km. Analysis techniques employed are discussed in Bendat and Piersol (1966) and Blackman and Tukey (1958). (In this case "power" is defined in terms of wavelength and amplitude.) Wave-

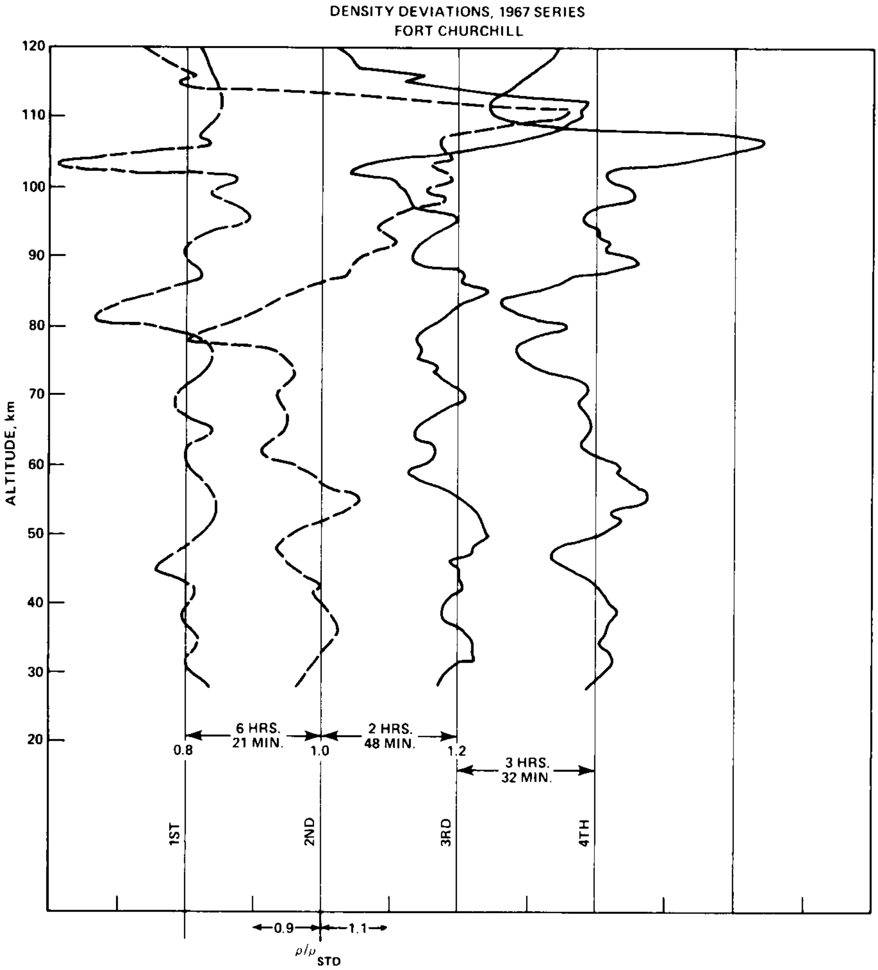

Fig. 1. Measured density deviations for 1967 Ft. Churchill series.

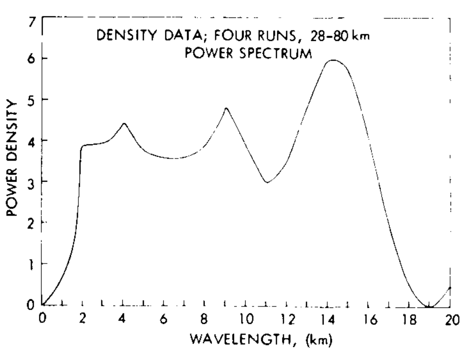

Fig. 2. Power spectral density versus wavelength for experimental deviations, 1967 series.

lengths between 2 km and 17 km are represented, with the primary peak occurring around 14 km, and the secondary peak around 9 km.

For the second test series, which was launched from Churchill (59° N), the observed density perturbation is shown as a solid curve in Fig. 3. The broken curve represents a gravity wave having horizontal wavelength of 60 km and a period of 20 minutes. Fig. 4 compares the wind pattern generated by the above gravity wave with the measurement of the first grenade sounding. Note that the vertical winds include values of some 10 m/s in the 80 km region. Justus and Edwards (1971) have reported measured vertical velocities

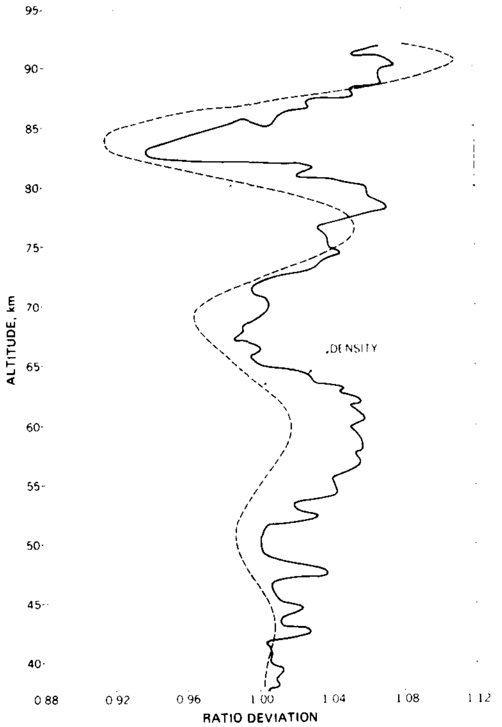

Fig. 3. The observed density perturbations (solid curves) over Churchill on January 13–14, 1970 compared with the perturbations calculated from theory (broken curves) as a function of altitude.

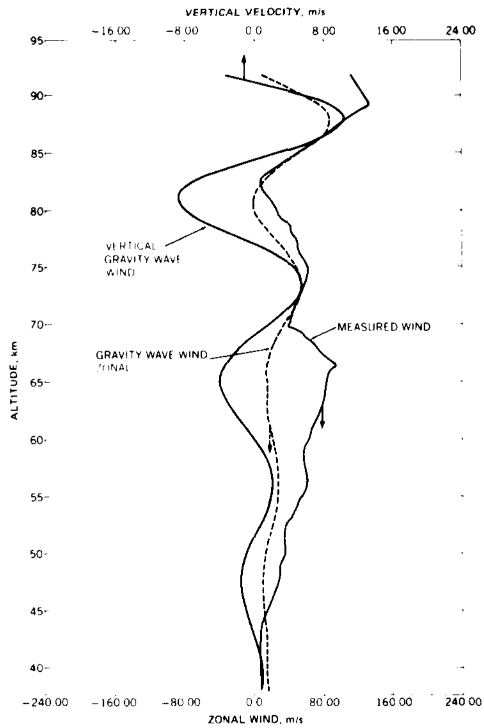

Fig. 4. The observed zonal wind component compared with the gravity wave wind.

on the order of 20 m/s at altitudes between 88–118 km. Although these measurements were made at a different latitude and time of year, they are at least comparable in magnitude. The Justus and Edwards data do confirm the existence of relatively large vertical velocities at high altitudes.

The third set of measurements which consisted of pitot and grenade soundings from Point Barrow (71° N) began with a pitot and a grenade launched 2 minutes apart. The temperature perturbations obtained from the pitot profiles are shown in Fig. 5 together with a theoretical gravity wave which was matched to the first perturbation for a best fit (by eye). The gravity wave structure is based upon the original match of the first pitot and allowed to propagate with time to correspond to the times of the observational data. The best match was found to have a horizontal wavelength of 70 km and a period of about 18 minutes, or 280 km and a period of 72 minutes. It is significant that only the first theoretical curve was fitted to the observed data, and that the remaining matches followed from calculation. Thus our data indicate that not only are the spatial density and wind structure measurements compatible with gravity wave theory, but also the expected behavior with time.

Fig. 6 shows a comparison between the observed wind pattern and the calculated wind pattern associated with the gravity wave matched to the first temperature perturbation. A mean drift wind of 40 m/s has been included. The measured wind is obtained from the grenade sounding, so it represents a series of values in which the winds were averaged over layers (2–3 km thick) between grenade explosions.

5. Discussion

Three series of soundings were carried out at high latitude sites during winter. The first series gave four essentially instantaneous vertical density traverses during a 13-hour period at Ft. Churchill. The density variations from the mean strato-

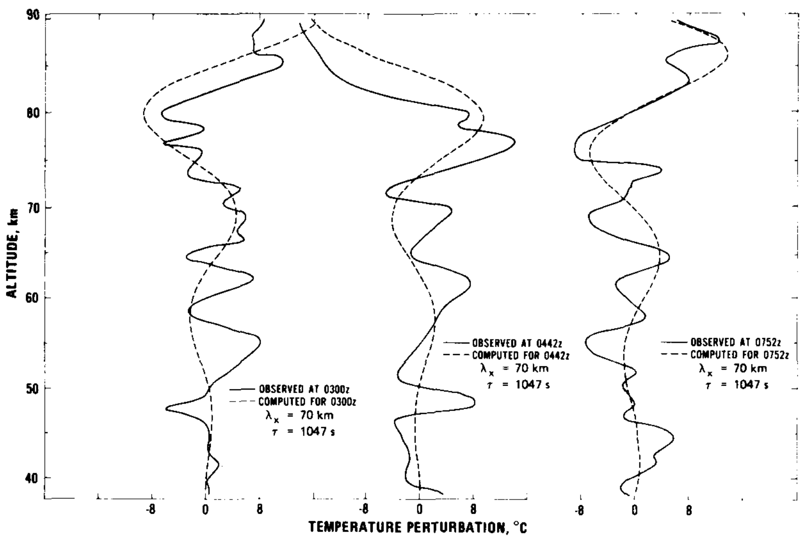

Fig. 5. 1971 series gravity waves matched to pitot temperature deviation.

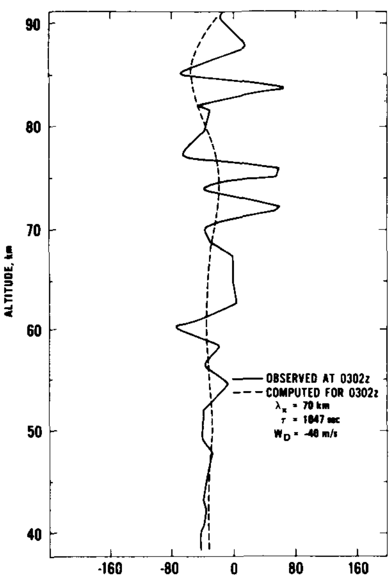

Fig. 6. Comparison between theoretical and observed wind patterns for 1971 series.

spheric conditions were matched by gravity waves having vertical wavelengths of 14–17 km. A reasonable fit to the data was obtained with a plane gravity wave characterized by a horizontal wavelength of 70 km and a period of 18 minutes or 280 km and 70 minutes. The wave amplitude increased with altitude, but at a rate much slower than the exponential growth predicted for undamped waves. Thus one must conclude that the waves were heavily damped as they propagated upward through the atmosphere. The term "damped" in this case is taken to include general wave dissipation by various possible mechanisms, including non-linear effects of the gravity waves themselves. Following Lindzen (1968) we have looked at the Richardson number, and found it to be small or negative between approximately 53 km and 85 km. Thus, it is quite possible that dissipation in this height range is largely the result of non-linear effects in the gravity waves. Such an interpretation is certainly consistent with the observed slow vertical growth rate below 85 km.

Gossard (1962) observed gravity waves in the troposphere, and found the period to vary between 15 minutes and 120 minutes. The horizontal wavelength for waves of 15-minute period was 19 km, and for 2-hour period, it was 150 km. The difference between our observations and those of Gossard may be explained by assuming that tropospheric waves with short vertical wavelengths are damped out. In fact Gossard (1962) found that the maximum leakage into the upper atmosphere occurs at periods of 10 to 20 minutes, starting with a white energy spectrum in the troposphere. Our value of 18 minutes is thus consistent with

Table 4. *Horizontal phase velocity 200° K; 18-minute period*

λ_z (km)	λ_x (km)	V_{px} (m/s)	V_{pz} (m/s)
5	18.2	16.9	4.6
10	36.4	33.7	9.3
15	54.4	50.4	13.9
20	72.3	67.0	18.5
25	90.0	83.3	23.1

Gossard's prediction. Gossard found a horizontal phase speed of approximately 21 m/s. For an 18-minute period and 200°K, the Table 4 relates our estimated horizontal phase velocity, V_{px}, to vertical wavelength, λ_z. 200 degrees K was chosen because it is approximately the temperature at the bottom of our test region. Since V_{px} is essentially λ_x/τ, it remains constant as long as the above ratio remains constant, and is thus equally valid for the 280 km waves.

From noctilucent cloud studies, Witt (1962) observed characteristic wavelengths of 30–40 km, and of 75 km, the latter being very nearly the 70 km deduced in the present study. Witt (1962) also estimated the wave velocity with respect to a frame of reference moving with the cloud system, obtaining a range of 70 to 135 m/s. The agreement with the values given in our table is reasonable. Noctilucent clouds are formed in the 75 to 85 km region of the atmosphere.

Our results are also generally consistent with the discussion of internal atmospheric gravity waves at ionospheric heights presented by Hines (1960). Thus the 12-km vertical wavelength which Hines deduced from the meteor wind data of Greenhow and Neufeld (1955, 1959) is in reasonable agreement with our observations. Hines considered 125 m/s to be a typical horizontal phase speed and quoted the following experimental results. Munro (1958) found phase speeds to generally be in the range of 51–175 m/s, in agreement with both our deductions and Witt's (1962) noctilucent cloud observations. Heisler (1958) found phase speeds to range between 97–207 m/s. The phase speed agreement is remarkable considering that ionospheric heights range up to more than 100 km above the top of our observation regime. Even our longer period of 70 minutes is significantly shorter than the 200 minutes deduced by Hines (1960) from correlation studies of meteor wind trails. However, a careful reading of Hines' paper suggests that the 200 minutes is an upper limit to the period, rather than a most characteristic value.

The results of the third series confirmed the conclusions about vertical wavelength and amplitude of the first two series and the agreement of measured wind with gravity wave predictions. It was also possible to trace one gravity wave pattern through three consecutive samples, indicating that our period is reasonable. However, the fact that the data can be matched by both 70-km and 280-km horizontal wavelengths (corresponding to 18-minute and 70-minute periods, respectively) suggests one of three possibilities, namely (1) the 70-km value represents an aliasing error, which seems unlikely in view of Witt's noctilucent cloud observations, (2) the 70-km horizontal waves represent an interference pattern between waves of 280 km or longer wavelengths, an interpretation consistent with Witt's noctilucent cloud measurements, or (3) the horizontal wave packet contains both 70-km, 18-minute and 280-km, 70-minute waves. The last interpretation disagrees with Hines' 200-minute suggested period but agrees with Gossard's tropospheric measurements. Our data cannot distinguish between explanations "2" and "3". However, Midgley and Liemohn (1966) suggest a wavelength of a few hundred kilometers, essentially in agreement with our 280-km wave. It should be mentioned that an excellent experimental technique exists for studying gravity waves at cloud level, namely observation of sequential satellite photographs. Such pictures should yield both the horizontal wavelength and the horizontal phase velocity relative to the ground.

It might be noted that Lindzen (1971) showed that knowledge of vertical wavelength and period can be used to estimate vertical eddy transport coefficients. Our estimated vertical velocities in the 80-km region are in the order of 2.5 to 10 m/s, compared with 1 m/s assumed by Lindzen from tidal theory. However, he divides his vertical velocity by a number N, characteristic of the particular transport process considered. N is the lifetime of the oscillation in cycles to the nearest integer. From the variability of tides revealed in radio meteor data, Lindzen suggests a value of 10–20 for N. For his 6-hour gravity wave, Lindzen (1971) takes N to be 5. For a 1-hour period, our vertical velocity is 2.5 m/s. Keeping N at 5, and using Lindzen's formula for estimating eddy diffusivity one obtains

$$D \approx \left(\frac{0.5}{5}\right) \quad (2.5 \times 100\,\text{cm/s})\,(3 \times 10^5\,\text{cm})$$

$$= 7.5 \times 10^6\,\text{cm}^2/\text{s}$$

where

$$D \approx \left(\frac{0.5}{N}\right) \quad (w) \quad \left(\frac{\lambda_z}{2\pi}\right)$$

For the 18-minute waves, the value for D becomes 3.0×10^7 cm²/s.

Hodges (1969) has estimated the effective eddy diffusivity associated with gravity waves which reach an amplitude where they generate breakers and thus considerable turbulence. Considering a gravity wave having a vertical wavelength of 16 km, the D_{max} value for $\lambda_x = 70$ km is 7.0×10^7 cm²/s, and for $\lambda_x = 280$ km it is 2.0×10^7 cm²/s. These values are approximately 2.5 times as large as what one estimates using the Lindzen approximation. However, the agreement must be considered good, considering the uncertainty in the quantity N. Furthermore, the observed waves do have some growth with altitude, while Hodges' value of eddy diffusivity would result in no growth with altitude.

The final mystery is why the waves appear to be coming out of the east, when everybody knows that the prevailing winds are westerly. The answer in this case is quite simply that the prevailing winds above 45 km, i.e., in most of the region considered, are in fact easterly, even though the tropospheric and lower stratospheric winds are westerly. In fact it is quite probable that the gravity waves are generated in a stratospheric shear zone where the winds change from westerly to easterly.

6. Appendix

Symbols

ω = circular frequency of the wave
a = local sound speed
k_0 = ω/a
γ = ratio of specific heats
$\omega_B = g/a\sqrt{\gamma - 1}$ = Brunt–Väisälä frequency
$\omega_A = \gamma g/2a = a/2H$
g = acceleration due to gravity
H = pressure scale height
$\mathbf{U}$ = wind velocity of background field
$\mathbf{k}$ = propagation vector
$k^2 = k_x^2 + k_z^2$
P = static pressure
P^0 = stagnation pressure
ρ = density
u = velocity
λ_z = vertical wavelength
λ_x = horizontal wavelength
τ = wave period

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ВЕРТИКАЛЬНЫЕ ПРОФИЛИ ТЕМПЕРАТУРЫ И ПЛОТНОСТИ В АРКТИЧЕСКОЙ МЕЗОСФЕРЕ, АНАЛИЗИРУЕМЫЕ КАК ГРАВИТАЦИОННЫЕ ВОЛНЫ

С трех высокоширотных мест зимой были проведены три серии ракетных зондирований. В первой серии в течение периода 13 часов из Форта Черчилль (Канада 59° с.ш.) 31 января и 1 февраля 1967 г. были запущены четыре трубки Пито для измерения давления. Вторая серия, состоявшая из одного измерения трубкой Пито и двух гранатных акустических зондирований, была проведена в течение трехчасового периода 13–14 января 1970 г. Независимо были измерены профили ветра и температуры и один профиль плотности для получения термодинамической структуры, структуры ветра и, таким образом, их взаимозависимость в мезосфере. Третья серия измерений была проведена из Пойнт Бэрроу, Аляска (71° с.ш.) 6 декабря 1971 г. Эта серия состояла из пяти зондирований, из которых два первых и два последних зондирования состояли из измерений давления трубкой Пито и гранатных акустических зондирований. Профили температуры из всех зондирований в каждой серии были осреднены, и гладкая кривая (или серии гладких кривых) были проведены через точки. Была рассчитана гидростатическая атмосфера, основанная на осредненных измеренных профилях температуры, и отклонения от среднего строения атмосферы были проанализированы в терминах теории гравитационных волн. Вертикальная длина волн в отклонениях была 10–20 км, причем амплитуды волн медленно росли с высотой. Экспериментальные данные были согласованы с вычисленными гравитационными волнами с периодом от 15 до 80 минут и горизонтальными длинами волн от 60 до 280 км. Наша интерпретация в общем согласуется с результатами других исследователей, которые изучали гравитационно-акустические волны в атмосфере. Измерения ветра согласуются с термодинамическими измерениями. Результаты также указывают на то, что гравитационные волны распространяются с востока на запад с горизонтальной фазовой скоростью, равной приблизительно 60 м/с.